SAND2012-6491C

Focusing a radio signal and simultaneously nulling it at another location using time-reversal: Experimental results

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***Abstract*—The time-reversal beam-forming technique utilizes the multipath in a cluttered environment to focus beyond the Rayleigh limit. This method makes use of the reciprocity of wireless propagation channels. Time-reversal can also be used to null signals, either to reduce unintentional interference or to prevent eavesdropping. Previous analytical work has also shown the ability to focus a signal at a location while simultaneously nulling it at a different location. We now present experimental results showing time-reversal focus and nulling in a cluttered environment.** [1]

I. INTRODUCTION

Time-reversal signal processing is a spatial focusing technique that utilizes the reciprocity of wireless channels. A signal received in a complex environment will have undergone multiple reflections, refractions, and scattering. It consists of the sum of multiple time-delayed and attenuated versions of the original signal, i.e., the channel is time dispersive. When the received signal is time-reversed and re-transmitted, the different time-delayed components go through the same channel in reverse and converge on the original source location. This convergence occurs in both space and in time. The time-reversal operation is the convolution of a channel with its time-reversed version.

The time-reversal technique has some practical benefits. It does not require knowledge of the receiver location and does not require line-of-sight. Increased multipath increases the focusing ability of the channel. In a physical context, the clutter in the environment is beneficially used to create a virtual antenna aperture that increases focusing ability.

This technique was first proposed for use in acoustics and has been under active exploration [1]. Classically, the focusing ability of an antenna depends on its size and is limited by the Rayleigh diffraction limit. In the last decade, experimental proof-of-concept articles in *Science* [2], and *Physics Review Letters* [3] showed that it is possible to focus beyond the diffraction limit in a spatially cluttered environment using time-reversal techniques. Similarly, phase-conjugate arrays, a narrow-band approximation to time-reversal, have been used to obtain focus resolution beyond the Rayleigh limit with microwaves [3].

In practical applications, it is desirable to focus a signal at the intended target while nulling it at unintended user locations so that co-channel interference to the unintended users can be decreased. A simple and optimal technique for accomplishing this has been presented previously [4].

The spatial and temporal focusing due to time-reversal depends on the physical channel, i.e., there is a strong dependence on the geometry of the environment. Thus, evaluation of this technique using statistical or estimated channels does not give a complete picture of its operation in a real physical environment. In this paper, we present experimental results for this technique in a real multipath-rich environment.

Section II briefly describes the application of time-reversal to spatial focusing and nulling. Section III shows experimental results for the performance of time-reversal focus and nulling in a complex environment.

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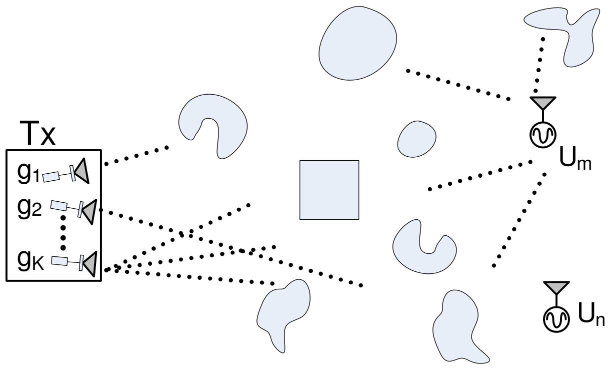


Fig. 1. Time reversal transmitter and receiver.

Characteristics such as focusing ability, simultaneous focus and nulling, etc are examined.

II. Time-Reversal Focusing

Consider the array transmitter, *Tx*, with K elements, as shown in Figure 1 (Note that the K array elements do not have to be in a regular geometric arrangement). In a time-reversal system, an initial probe pulse, $p(t)$, is transmitted by the intended receiver, U_m. The pulse received by *Tx* is

$$\mathbf{y}(t) = p(t) * \mathbf{h}_m(t). \tag{1}$$

$\mathbf{h}_m(t)$ is an array of channels, $h_{m,k}(t)$, where $h_{m,k}(t)$ is the channel between the receiver, U_m, and the k^{th} element of Tx. $\mathbf{y}(t)$ is the array of received signals at Tx.

Tx then transmits the time-reversed version of $\mathbf{y}(t)$, $\mathbf{y}_{tr}(t) = \mathbf{y}(-t)$. The receiver U_m receives the signal,

$$\begin{aligned} z(t) &= \sum^{K} \mathbf{y}_{tr}(t) * \mathbf{h}_m(t) = \sum^{K} \mathbf{y}(-t) * \mathbf{h}_m(t) \\ &= \sum^{K} p(-t) * \mathbf{h}_m(-t) * \mathbf{h}_m(t) \\ &= p(-t) * R_{hm}(t), \end{aligned} \tag{2}$$

where $R_{hm}(t)$ is the autocorrelation of the channel (from the transmitter array elements to U_m).

Increased complexity in the environment increases the randomness of $\mathbf{h}_m(t)$, which increases the auto-correlation peak (this is indicative of sharp focus). In imaging or detection applications, *Tx* illuminates the region and $p(t)$ is reflected from the target. In communication applications, $p(t)$ is a known probe and the transmitter *Tx* uses the channel, $\mathbf{h}_m(t)$ to transmit a new information signal using the beam-forming weights, $\mathbf{g}(t) = -\mathbf{h}_m(t)$.

In practical usage, it is desirable to focus on one user while nulling the signal at another [5]. An optimal technique for this exists [6]. For the case of a single focus location and a single null location this can be simplified to a very intuitive result in the frequency domain [4].

$$\mathbf{g}(\omega) = \gamma \begin{bmatrix} \frac{h^*_{m,1}(\omega)}{\left\|h_{n,1}(\omega)\right\|^2} \\ \frac{h^*_{m,2}(\omega)}{\left\|h_{n,2}(\omega)\right\|^2} \\ \vdots \\ \frac{h^*_{m,K}(\omega)}{\left\|h_{n,K}(\omega)\right\|^2} \end{bmatrix}, \tag{3}$$

where γ is a normalization constant. where $h_{n,k}$ is the channel between the null location, U_n, and the k^{th} antenna element of *Tx*.

The optimal beam-forming in this case depends on the known channel to the focus location but does not require complete knowledge of the channel to the null location. Only the power spectral density (PSD) of the channel to the null location is needed. This is a useful result, as the receivers at the null location may be part of a different communication system and may not be cooperative. But since only the PSD of the channel is important, a simple spectrum measurement will suffice.

III. Experimental Results

Experimental evaluation of time-reversal consisted of measuring real channels between transmitters and receivers. The channels were measured in a static environment (no movement in the environment during a measurement). Once this was done, the performance of the time-reversal algorithms could be evaluated on the real measured channels.

Experiments were made for different arrangements of the physical environment. For each test setup a channel matrix between an array of transmit antennas and an array of receive antennas was measured. Time-reversal was evaluated using these channel matrices.

A. Experiment setup

The laboratory experiments were conducted in an electro-magnetically shielded room with intentionally placed clutter (Figure 2). Obstructions (chairs, bookcases, metallic containers, benches, lab equipment, etc.) were placed to create a multipath rich environment (Figure 3). Transmit antennas were mounted on tripods,

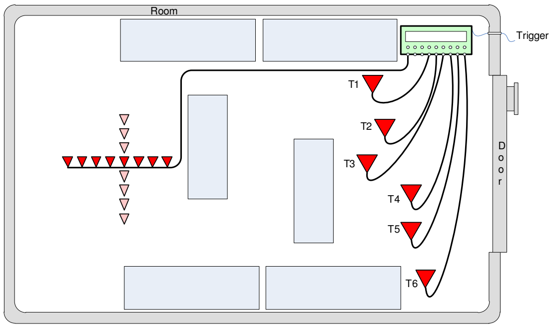
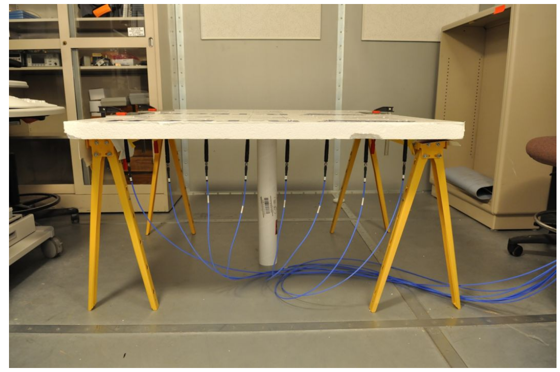


Fig. 2. Laboratory layout for time-reversal experiments

Fig. 3. Electromagnetically cluttered test environment

but the mounting was not controlled (Figure 4). This was intentional since the time-reversal technique does not depend upon controlled inter-antenna spacing, height, or orientation. The test equipment was controlled from the outside of the shielded room. Care was taken to ensure that nothing was moved in the environment during a measurement sequence.

Fig. 4. Transmit antennas are placed in an irregular array to demonstrate that time-reversal does not require specific spacing, height, or even orientation of transmit antennas



(a) Linear array of receive antennas in Styrofoam

(b) Receive antenna array with a grid spacing of 13.5 cm

Fig. 5. Receive antennas located in an array

Figure 2 shows six transmit antennas and eight receive antennas. The 8 receive antennas were placed in different arrangements (shown in light red). They were supported in place using styrofoam (Figure 5).

B. Channel measurement

The channels between the transmit and receive antennas were measured using a network analyzer. A channel measurement can be obtained by measuring the complex transfer function between ports using scattering parameters (S-parameters) [7]. A network analyzer sweeps the scattering parameter measurement across frequency. For a channel measurement, it is essential that nothing is disturbed (channel is kept static) during a single measurement sweep.

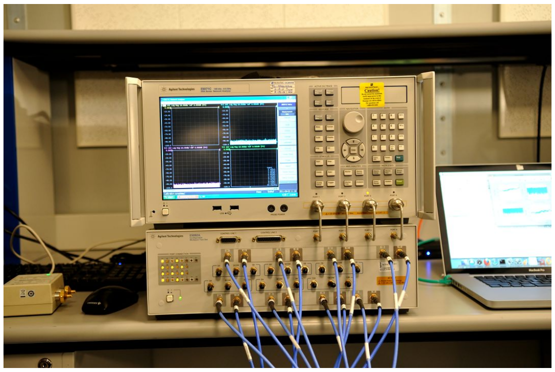


Fig. 6. Network analyzer and multi-port test set for measuring an array of channels

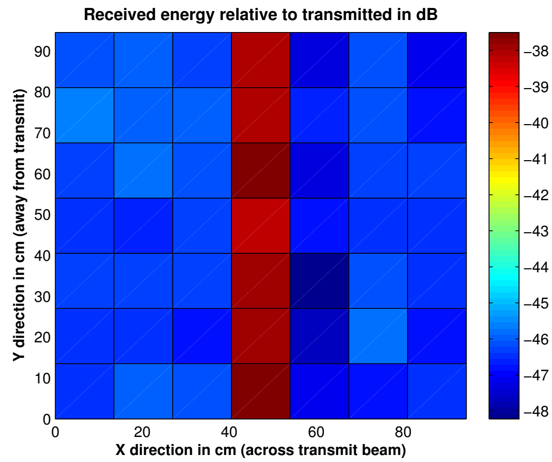


Fig. 7. Signal focusing parallel to the transmit antenna plane

With a four-port network analyzer, we can measure channels between a maximum of four antennas. A multi-port test set (which is a bank of RF switches) can be used to increase the effective number of ports. For this time-reversal characterization, the combination of an Agilent E5071C vector network analyzer (VNA) and an Agilent E5092A multiport test set (MTS) (Figure 6) was used. This setup allowed us to measure the channels between eight transmit and eight receive antennas.

Channel measurements were taken in the range of 5 and 6 GHz. A resolution bandwidth of 1 kHz was used to provide large dynamic range in measurement. High-quality RF cables were used to keep the phase stable during measurement. The combined setup of VNA, MTS and cables was calibrated before the measurement run.

C. Focusing Ability

To test focusing ability, the channels to an 8x8 grid of receive locations were measured. Eight receive antennas were used to measure one horizontal row at a time. A horizontal row, for our purpose, is visually parallel to the plane of the transmit antennas and perpendicular to the direction of signal transmission. Time-reversal focusing was applied to the channels one row at a time. The focus spot was always the center of the row. Figure 7 shows the focusing ability in the horizontal direction. The difference in energy delivered to the center of the grid versus any of the side elements is approximately 8 dB. Another observation made during this measurement was that once a row of antennas was moved, it was difficult to re-place it identically since even small cable movements affected the channel. This could be alleviated partially by using foil backed Styrofoam which decreased the effect of the cables on the channel measurements.

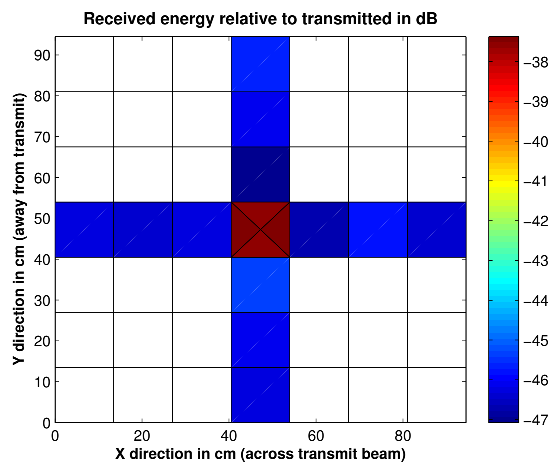


Fig. 8. Experimental performance of time-reversal signal focusing in X and Y directions (grid spacing of 13.5 cm). The horizontal and vertical receive array placements do not result in the same energy at the center since the placement of the antennas affects the channels. The top and bottom quadrants of the center square show the signal at the center when the receive array is in the vertical arrangement. The side quadrants show the signal at the center when the receive array is in the horizontal arrangement.

Further measurements are shown using only linear arrays of 8 receive antennas. Figure 8 shows the focusing in the horizontal (parallel) and vertical (away) direction from the transmit array. The focusing ability is very similar in both directions. In all cases, the intended focus location is the central grid point. It was also seen that the focusing ability was independent of the particular focus point that was chosen.

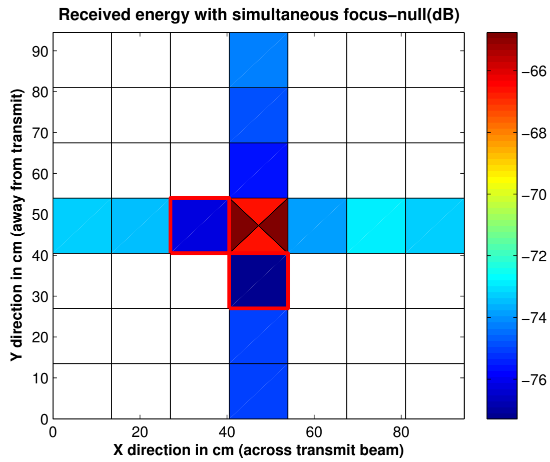


Fig. 9. Experimental performance of simultaneous focus and null in X and Y directions (grid spacing of 13.5 cm). Nulling is performed on the regions outlined in red.

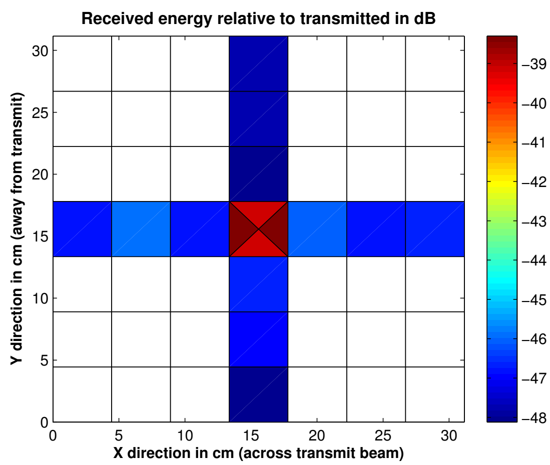


Fig. 10. Experimental performance of time-reversal signal focusing in X and Y directions with close spacing of receive antenna array (grid spacing of 4.5 cm).

D. Simultaneous Focus and Null

The experiment setup used for focusing was also used to test simultaneous focus and nulling. A linear horizontal array and a linear vertical array were used to measure the channels for this purpose. Time-reversal is used to focus energy on the center and null out the closest adjacent grid point (the regions outlined in red) (Figure 9). It is seen that at the null locations, the signal is decreased an additional 3 dB. Nulling at farther locations from the central focus point is even easier, since those channels are even less correlated with the channel to the focus point.

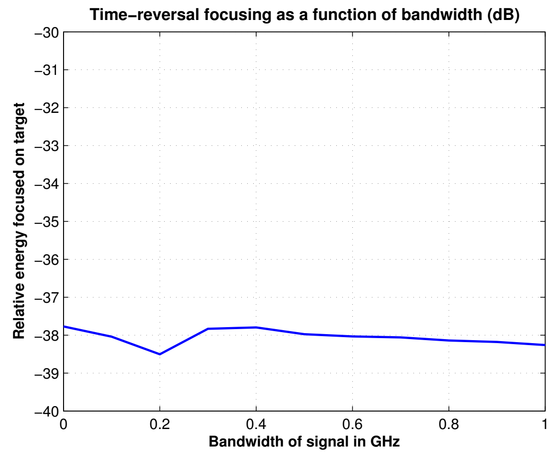


Fig. 11. Experimental performance of time-reversal signal focusing vs bandwidth.

Effect of increased grid resolution: For this test, increasing the grid resolution and using a smaller array smaller array (4.5 cm grid-spacing) provided very similar performance as the larger array (Figure 10). At these short distances, the metallic antennas in close proximity to each other are well within the near-field,

$$dist_{nearfield} = \frac{2D^2}{\lambda} \approx 80\,cm, \tag{4}$$

where, D is the largest dimension of the antenna and λ is the wavelength. The interaction between them creates enough channel complexity to allow for increased spatial resolution [2].

Effect of bandwidth on focusing ability: Using the channel data, we can also compute the performance of time-reversal if we were to vary bandwidth (Figure 11). We see that time-reversal performance is not bandwidth dependent. Time-reversal can work even in a narrow band system. For a narrow band system, time-reversal is equivalent to phase conjugation.

Number of antennas vs focusing ability: The channel data can also be used to compute the performance with respect to the number of transmit antennas (Figure 12). As seen in simulations, experimental results show that increasing the number of antennas increases time-reversal performance. Though this is usually the case, there are specific channels for which this may not be the case.

E. Comparison with free space

The time-reversal technique works in the presence of multipath as seen in the previous experiments. To

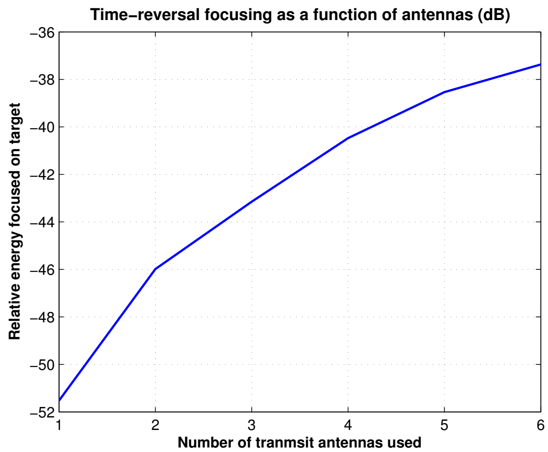


Fig. 12. Experimental performance of time-reversal signal focusing with varying number of antennas

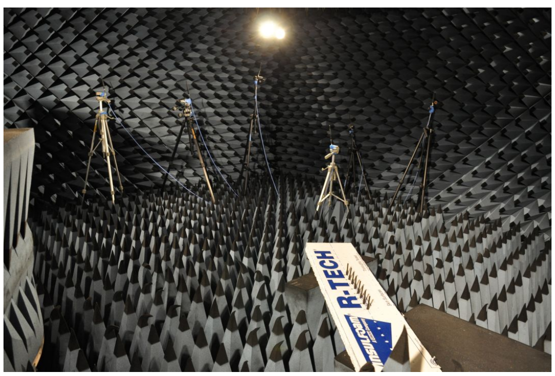


Fig. 13. Experiment setup in an anechoic chamber

contrast its performance in a multipath environment with its performance in a free space environment, experiments were also conducted in an anechoic chamber without the obstructions (Figure 13). Some sources of reflections such as tripods and cables could not be avoided.

Horizontal (across) and vertical (away) measurements were made with the 8 receive antenna array. We can compare the performance in the anechoic chamber (Figure 14) with the performance in the multipath environment (Figure 10). In the anechoic chamber about 5 dB of focusing selectivity is obtained as opposed to the 8 dB in the multipath environment. Also, note that the anechoic chamber is not completely free of multipath since the multipath caused by the receive antenna array is still present. Another thing to note is that even though the distance between the transmit array and receive array is about the same in both experiments, the absolute energy received in the multipath environment is approximately 25 dB higher than in the anechoic chamber.

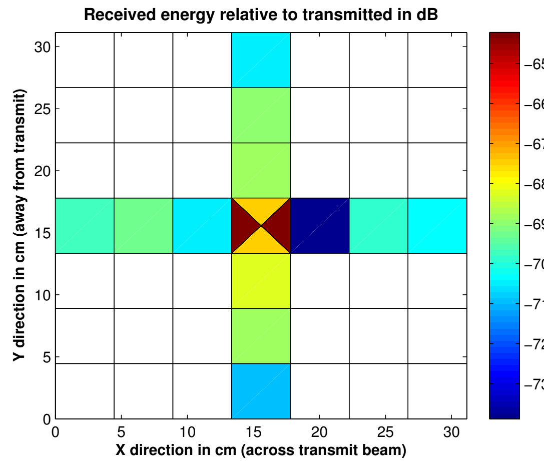


Fig. 14. Experimental performance of time-reversal signal focusing in an anechoic chamber (grid spacing of 4.5 cm)

IV. Conclusion

Time reversal signal processing can be used to focus energy at a target location while simultaneously nulling energy at a different location. The performance of time-reversal is very dependent on the characteristics of the physical channel. The experimental results in this paper using real measured channels show that the focus and null can be done with high spatial resolution, as much as 11 dB within a 4.5 cm distance.

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